INVITED PAPER

Advanced NDE and QA for Ensuring Quality and Integrity of Critical Components in Nuclear Industry

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Introduction

Energy is the enabler for all social and economic developments and growth of civilization. For a country like India with a population of about 1.2 billion and a average growth rate of about 8 % annually (likely to increase further), energy is a central issue. Based on the projected demand and India's energy resource base, it is now well established that nuclear energy using the vast thorium reserves is the only viable alternatively presently that could ensure the energy security of the nation. The key to the successful utilisation of the vast thorium reserves lies in the development of fast breeder reactors.

The Indira Gandhi Centre for Atomic Research (IGCAR) has been established with the mandate to develop fast reactor technology so that FBRs can be deployed for generating electricity in the decades to come. As part of this strategy, a 40-MW(th) test reactor, the Fast Breeder Test Reactor (FBTR),was constructed and commissioned in 1985. This reactor has successfully operated for over 25 years without any major incidence using the unique and new carbide fuel which has achieved a burnup of more than 157 GWD/t an international benchmark. This test reactor has been utilised for fuel development, reactor physics experiments and irradiation of structural materials. This coupled with the extensive R&D efforts in all aspects of FBR technology has laid the foundation for the design and development of a 500-MWe Fast Breeder Reactor (FBR). Construction of the 500 MWe FBR started in 2002. It is now in an advanced stage and is expected to be completed by 2012. This FBR will be the forerunner of a series of FBRs that are to follow soon. Success of fast reactor technology demands a coherent multidisciplinary approach, focused research in basic science and engineering and robust technologies for manufacturing and inspection. This is depicted schematically in Fig. 1.

Austenitic stainless steels have been chosen as the major structural materials for the currently operating and planned FBRs all over the world in view of their adequate high temperature mechanical properties, compatibility with liquid sodium coolant, good weldability, availability of design data and above all the fairly vast and satisfactory experience in the use of these steels for high temperature service. Table - 1 summarises the candidate material used for some of the critical components of fast breeder reactor.

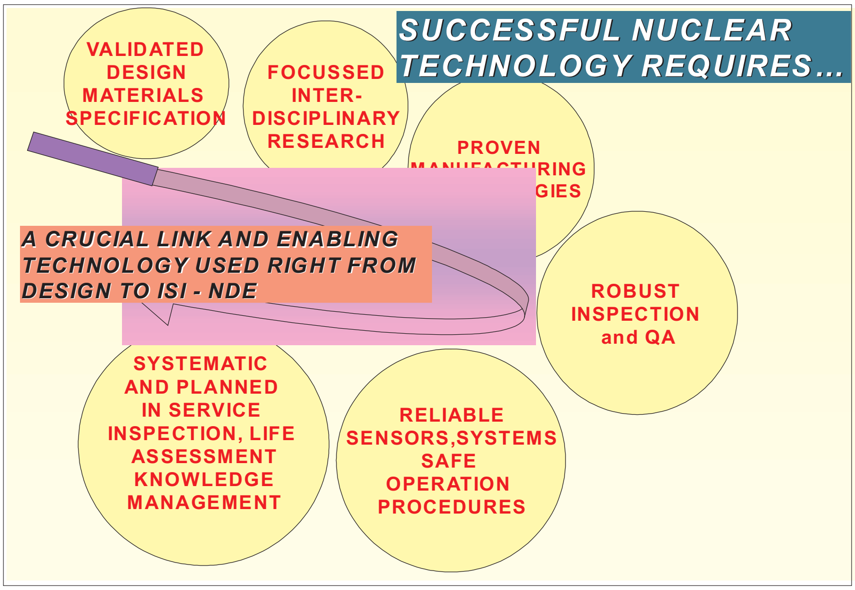

Fig. 1: Multidisciplinary approach for success in fast reactor technology

Table 1: Candidate material for some critical components of 500 MWe FBR.

Sl.No.	List of Components	Material of Construction
1	Main Vessel	AISI 316LN
2	Safety	AISI 304LN
3	Core Support Structure	AISI 316LN
4	Grid Plate	AISI 316LN
5	IHX	AISI 316LN
6	Primary & Secondary sodium Pumps	AISI 316LN
7	Steam Generators	9 Cr- 1 Mo
8	Secondary Circuit Tanks	AISI 304 LN

The reliability of any component or product is determined by its conformity to specifications and its ability to perform the required functions under stated conditions for stated period of time. This can best be achieved through stringent application of quality management practices. In the nuclear industry, quality management practices start right from the initial stages of design, raw material and consumable, specification and procurement through fabrication and preservice inspection. In this paper, we highlight broadly the Quality Management System that has been adopted at IGCAR. The paper also outlines the critical role of advanced NDE in ensuring the quality and integrity through the case study of application of advanced phased array techniques for evaluating the outer shell welds of steam generator of PFBR.

Brief Description of 500 MWe FBR

Fast Breeder Reactor (FBR) is a pool type 1250MWt / 500 MWe, Metal Oxide (MOX) fuelled (PuO_2-UO_2), sodium cooled reactor presently under advanced stage of construction at Kalpakkam. The overall flow diagram of the 500 MWe FBR comprising of the core, reactor assembly and heat transport system and balance of plant is shown in Fig.2. The core of the reactor consists of fuel subassemblies containing (U,Pu) mixed oxide fuel, which are immersed in a pool of liquid sodium. The heat transport system consists of a primary sodium circuit, secondary sodium circuit and steam-water system. The reactor assembly consists of core, grid plate, core support structure, main vessel, safety vessel, top shields and absorber rod drive mechanism. The main vessel of reactor assembly houses basically hot and cold sodium pools, separated by inner vessel. Both the pools have a free sodium surface blanketed by argon. The reactor core consists of 1758 subassemblies including 181 fuel subassemblies. The nuclear heat generated in the core is removed by circulating sodium from cold pool which is at 670 K, to the hot pool which is at 820 K. The sodium from hot pool transports the heat to four intermediate heat exchangers and joins back to the cold pool. While the circulation of sodium from cold pool to hot pool is maintained by two primary sodium pumps, the flow of sodium through intermediate heat exchangers is driven by a level difference (1.5 m of sodium) between the hot and cold pool free surfaces. The heat from intermediate heat exchangers is transferred to eight steam generators by sodium in the secondary circuit. Steam produced in steam generators is supplied to turbo-generator.

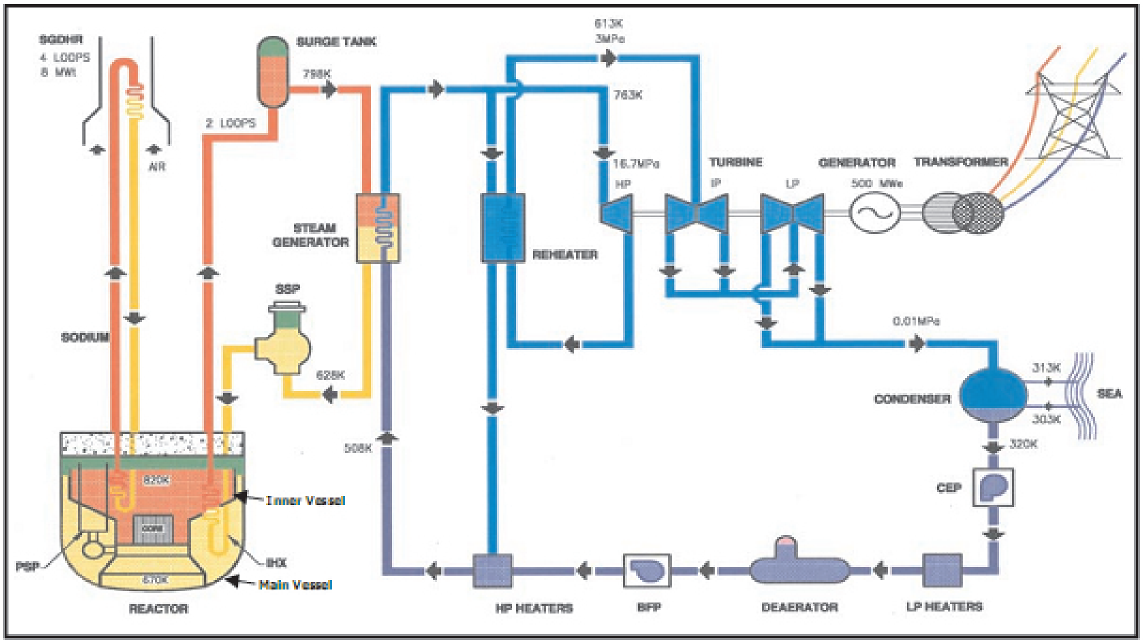

Fig. 2: Schematic flow diagram of the 500 MWe FBR

Quality Management Considerations

The reliability of any component or product is determined by its conformity to specifications and its ability to perform the required functions under stated conditions for stated period of time. This can best be achieved through stringent application of quality management practices. The typical quality management system in a nuclear industry is depicted in Fig. 3.

Fig. 3: Typical Quality Management System in Nuclear Industry

In the nuclear industry, quality management practices start right from the initial stages of design, raw material and consumable specification and procurement through fabrication and preservice inspection. The rigorousness with which these are practiced can vary from reactor to reactor or country to country. In India, especially in the design and construction of the fast reactor, great emphasis has been placed on the quality management system. The success of this system can be gauged by the fact that the 40 MWt Fast Breeder Test Reactor at Kalpakkam has operated successfully without any major incidences for 23 years. With the rich experiences of FBTR and the strong R & D base established at IGCAR for fast reactor technology, India took a quantum leap from 40 MWe FBTR to launch of the 500 MWe Fast Breeder Reactor.

500 MWe FBR is a first of its kind technology. To ensure high safety and reliability of the components, a well structured and comprehensive QA approach has been adapted to plan, implement during all stages of manufacture such as material inspection, welding and process control, process qualification, fabrication, NDE, sub-assembly & assembly and performance testing in the case of the FBR components. The fabrication specifications have been made much more stringent compared to the existing ASME codes of practice. Table - 2 typically compares the acceptance criteria in the case of radiographic examination of welds in the main and safety vessel.

Table 2: Comparison of acceptance criteria for Radiographic examination of welds

Sl. No.	ASME Sec.III, Class-I Following are unacceptable	500 Mwe FBR Following are unacceptable
1.	Any type of crack, lack of fusion and lack of penetration.	Any type of crack, lack of fusion and lack of openetration.
2.	Any elongated indication which has a length greater than the values given below. a) 6 mm for ≤ 19 mm b) t/3 for t above 19 mm and up to 57 mm inclusive c) 19 mm for t over 57 mm	Any elongated indication which has a length greater than the values given below. a) 1.5 mm for t < 6 mm b) 3 mm for t from 6 mm up to 10 mm c) t/3 for t above 10 mm and up to 50 mm d) 20 mm for t>50 mm
3.	Any group of indications in a line that have an aggregate length greater than t in a length of 12 t Note: Two neighbouring defects shall form a continuous defect if the distance between them is less than 6 times the length of larger of them.	Any line of slag inclusion where length total is more than "t" over a length of 12t Note: Two neighbouring defects shall form a continuous defect if the distance between them is less than 6 times the length of shorter of them.
4.	Rounded indication in excess of that shown in Appendix VI	Any gas cavity if its greater dimension equal to (or) greater than values given below a) 1.5 mm t<6 mm b) 2 mm for t 6 mm and above up to 10 mm c) 2.5 mm for t above 10 mm and up to 25 mm d) 3 mm for t above 25 mm and up to 50 mm e) 4 mm for t >50 mm
5.	The total area of rounded indications as determined from the radiographic films shall not exceed 38.7 sq. cm in any 15.2 cm length of weld.	Any cluster (or) line of cavities affecting a length of weld exceeding 5 t (or) 50 mm (the smaller of two values is to be applied) Note: Two gas cavities are deemed to belong to the same cluster if the distance between them is less than 5 times the maximum dimensions of the large one Isolated tungsten inclusions whose greater dimension is a) > 1mm for t up to 6 mm b) > 1.5 mm for t above 6 mm

NDE of Welds during fabrication

The special design requirements of FBR component / vessel welds necessitates systematic and sequential stage inspection of weldments for its soundness and to achieve highest quality practicable. The QA, QC and inspection stages are so planned that there is 100% coverage of all welds. The various NDE methods used during stage and final weld inspection include Visual Examination (VE), Penetrant Testing (PT), Radiography, Ultrasonics and Helium leak testing. Visual Examination is one of the most simple and effective NDE methods for surface defects. VE was employed for inspection of root pass and final welds after flush grinding for all the butt weld joints. The weld joints were also tested using visible dye penetrant testing. An essential requirement for penetrant materials was that the halogen and sulphur content needed to restricted to less than 25 ppm and 1% by weight respectively. 100 % Radiography of all weld joints is one of the essential requirements of PFBR specification. The acceptance criteria for the weld joints is much more stringent compared to equivalent ASME Sec III, Class-I components as indicated in Table-2. Keeping in view the fact that the reactor needs to operate for more than 40 years, digital archiving of the radiographs pertaining to critical components have been undertaken. Special procedure for digitisation was evolved at the Quality Assurance Division based on extensive trials and subsequently implemented for 500 MWe FBR [1]. Wherever radiography was difficult due to configuration or problems of accessibility, ultrasonic testing was adopted. For the first time advanced UT technique - phased array was introduced for quality audit of the outer shell welds. This is described below.

Phased Array Inspection of PFBR components

Steam generators are the workhorses in any power plant. 500 MWe FBR has eight SGs. The steam generator of FBRs are designed with a single wall separating the water/steam from the sodium. The very high reactivity of sodium with water makes the steam generator one of the most critical components governing the safe and efficient running of the plant. Realising this, extensive technology development was undertaken by IGCAR to ensure robust design and mature quality assurance practices. In the steam generator (SG) of Fast Breeder Reactor, the transfer of heat from secondary sodium to water generates steam. Since the sodium-water reaction is exothermic and generates high pressure and hydrogen, the integrity of weld joints separating sodium and water/steam and the overall integrity of steam generator is of paramount importance. Thus, the tubes and the welds have to be inspected thoroughly. Innovative procedure based on microfocal radiography was successfully evolved and adopted for the evaluation of the critical tube to tube sheet welds [2]. Advanced ultrasonic testing techniques like phased array was applied to evaluate the shell side 12 mm thick butt welded joints as a part of quality audit. Phased array provides high speed electronic scanning without moving parts, improved inspection capabilities through software control of beam characteristics, inspection with multiple angles with a single electronically controlled probe and greater flexibility for inspection of complex geometries. Compared to conventional pulse echo techniques, phased array has higher probability of detection also.

A total weld length of 6 meter from various seams of the outer shell weld of SG was subjected to phased array ultrasonic examination as part of quality audit. This is the first instance that a core nuclear component is being evaluated by using phased array. The TD Focus Scan from AGR UK was the instrument used along with a 5 MHz frequency phased array probe having 16 elements with 0.6 mm pitch.

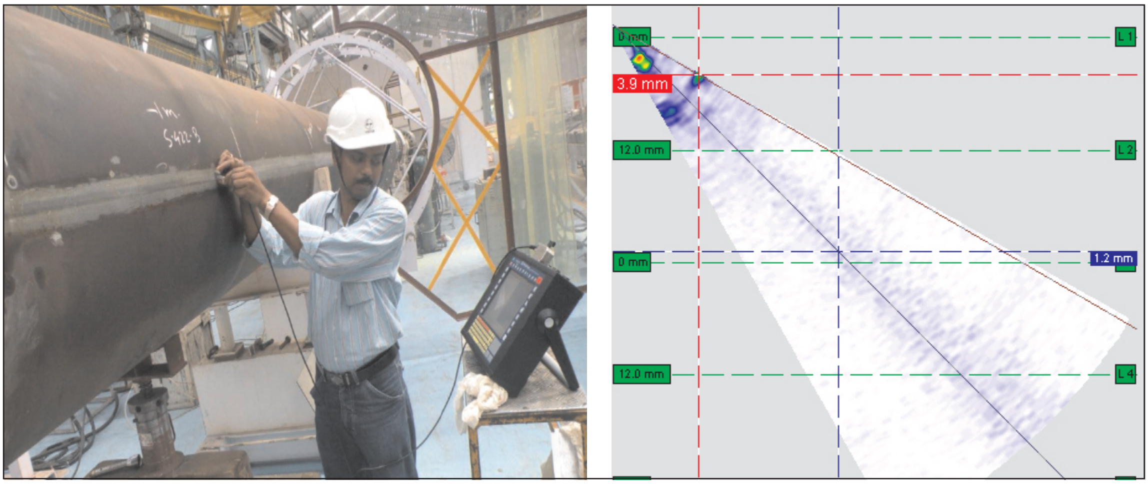

Fig. 4: (a) Phased array inspection of steam generator and (b) a typical phased array image of an LF

During the scanning indications were noticed at various locations. Fig. 4 (b) shows a typical LF detected in one of the sectors. The results were compared with the radiographic examination and pulse echo techniques and found to be satisfactory. When compared with the conventional pulse echo ultrasonic examination technique, it was found that there is a higher probability of detection and drastic reduction of scanning and evaluation time with phased array ultrasonic scanning.

Hexagonal wrapper tubes (Hexcan) made up of SS 316 LN house the fuel pins of the 500 MWe FBR. The hexcans are also used as reflectors. The quality assurance of welds in hexcans is of very important as failure of these welds in service may result in separation of fuel pins from the bundles and thus interfere with fuel subassembly unloading operation and/or failure of fuel pins leading to contamination of the coolant with fuel and radioactive fission products. Hence, stringent nondestructive examination of hexcan sheath welds is essential.

The complex geometry and large material thickness in the cross section of the welds as compared to the thickness of the sheath limits the sensitivity of the radiographic examination for detection of defects in these welds. Hence inspection using ultrasonic techniques is developed. Conventional pulse echo angle beam examination was not adequate for these welds since the scanning has to be carried out only from one side (thin side) of the weld. Hence a methodology based on phased array inspection has been developed and successfully applied. Fig. 5 shows the typical experimental setup and a indication from one of the hexcan welds.

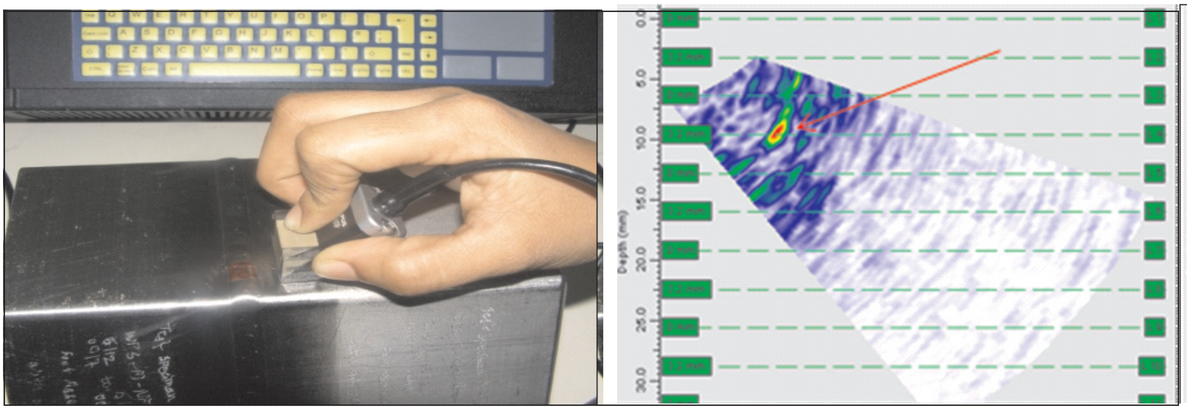

Fig. 5: (a) Phased array scanning of hexcan weld and (b) a typical lack of fusion image

Conclusion

Quality Management comprises of effective quality control, assurance and quality audit practices. In the nuclear industry, the great emphasis on safety and stringency of specifications requires innovative quality management practices. QM practices start from the cradle i.e. raw material specification. A well planned and comprehensive QA approach has adapted to ensure that the QA requirements of the 500 MWe FBR components is met during all stages of fabrication. A blend of conventional and advanced NDE techniques has been adopted to ensure the quality of the welds and components. This paper highlights the quality management practices being adopted. Two case studies pertaining to the successful application of an advanced ultrasonic testing - phased array inspection of outer shell welds of SG and hexcan welds has also been outlined.

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